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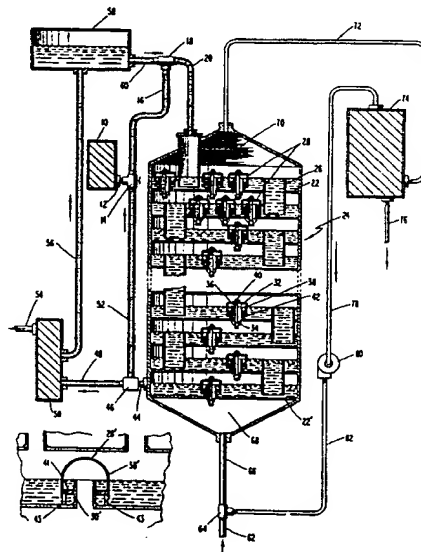
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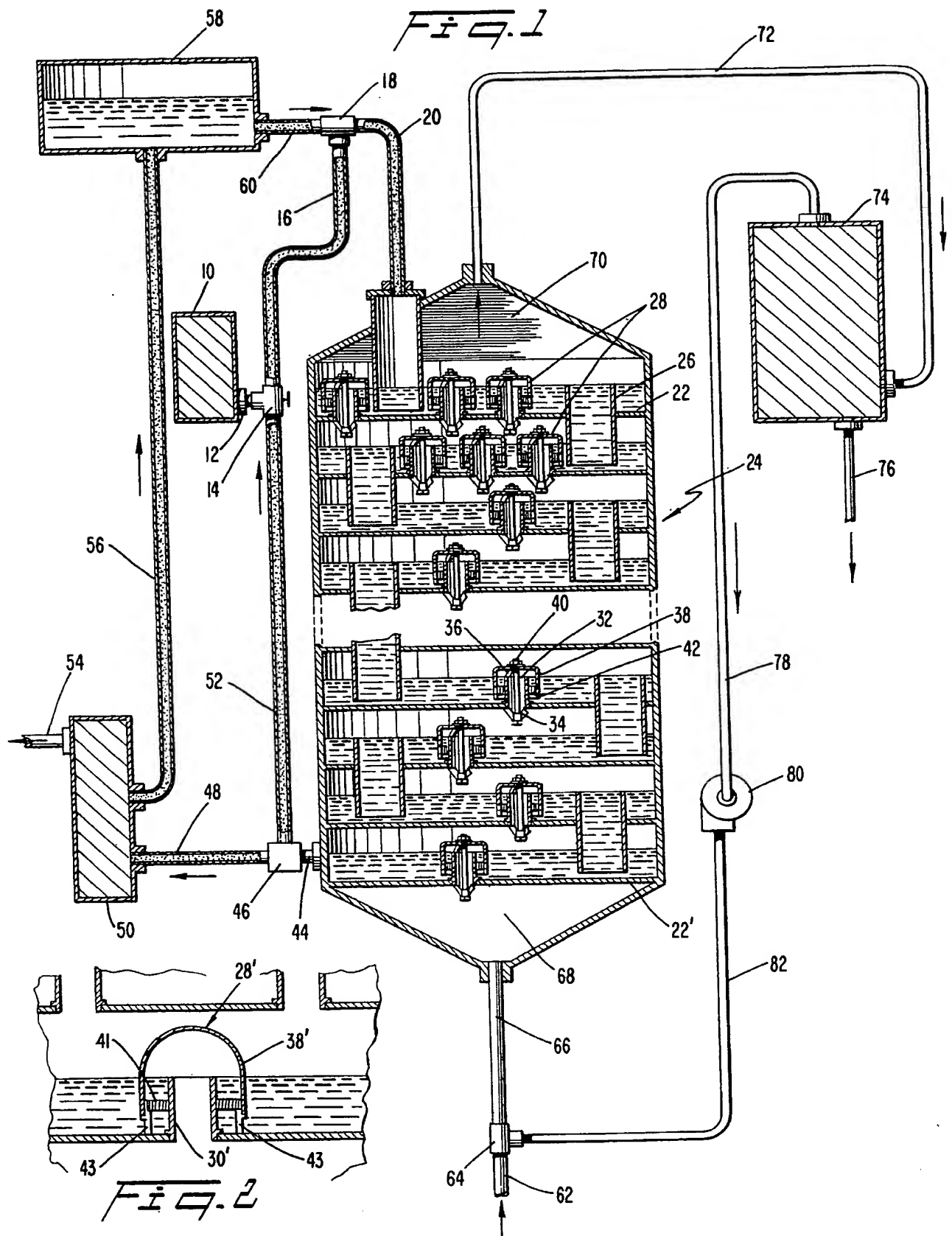
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㉕ **A low energy continuous process for increasing the oxidative state of an oxidisable organic substrate.**

㉖ A biocatalytic process for the conversion of an organic substrate comprise establishing a series of separate but intercommunicating sequential contact zones, as shown in Fig. 1, flowing a liquid composition comprising a biocatalyst successively through each of said zones from a liquid inlet zone to a liquid outlet zone, flowing a gas through each of said zones successively through a gas inlet zone to a gas outlet zone, in intimate countercurrent contact with the flowing liquid in each of said zones, flowing an organic substrate successively through each of said zones in intimate, reactive contact with said gas and with the liquid composition containing the biocatalyst, and recovering liquid effluent discharged from the liquid outlet zone and gaseous effluent discharged from the gas outlet zone, said recovered effluent comprising at least some of said organic substrate that has been converted to a different state.





"A low energy continuous process for increasing the oxidative state of an oxidisable organic substrate"

1  
2           The present invention relates to a continuous  
3 practical process for increasing the oxidative state of an  
4 oxidizable organic substrate, the process being characterized  
5 by low energy requirements. In particular, the process is  
6 concerned with the conversion of gaseous hydrocarbons  
7 into their respective corresponding alcohols, aldehydes,  
8 ketones, epoxides, and acids. More specifically, in one  
9 embodiment, the process is concerned with the oxidation of  
10 propylene to propylene oxide.

11  
12           Batch reactions have been described for the con-  
13 version of gaseous hydrocarbons into their corresponding  
14 alcohols, aldehydes, ketones, epoxides and acids,  
15 utilizing biocatalysts in the presence of oxygen. Although  
16 suggestions have been made that such processes could be  
17 practised on a continuous basis, no such practical process  
18 has been described or demonstrated.

19           The discovery and isolation of certain methylo-  
20 trophic microorganisms strains, that grow well under  
21 aerobic conditions in a culture medium in the presence of  
22 methane as the major carbon and energy source, is reported  
23 in U.K. patent application GB 2,018,822 A.

24           The methane-grown microbial  
25 cells possess a high content of protein. The cells, or  
26 enzyme preparations derived from the cells, are said to be  
27 useful in converting oxidizable substrates to oxidation  
28 products. In particular,  $C_1-C_6$  alkanes can be converted to  
29 alcohols, such as methane to methanol;  $C_3-C_6$  alkanes can be  
30 converted to the corresponding secondary alcohols and methyl  
31 ketones;  $C_3-C_6$  secondary alcohols can be converted to the  
32 corresponding methyl ketones; and cyclic hydrocarbons can be  
33 converted to cyclic hydrocarbyl alcohols, such as cyclohexane  
34 to cyclohexanol; and  $C_2-C_4$  alkenes selected from  
35           ethylene, propylene, butene-1 and butadiene,  
36 can be converted to 1,2-epoxides.

1 Cell-free extracts of certain of these hydro-  
2 carbon-utilizing microbes, including bacteria and yeasts,  
3 contain a nicotinamide adenine dinucleotide (NAD)-dependent  
4 secondary alcohol dehydrogenase (SADH). This enzyme  
5 specifically and stoichiometrically oxidizes  $C_3-C_6$   
6 secondary alcohols, such as 2-propanol and 2-butanol, to  
7 their corresponding ketones.

8 A process for the epoxidation of  $C_2-C_4$  alpha  
9 olefins and dienes, through the action of a particular kind  
10 of biocatalyst in the presence of oxygen, is described in  
11 U.K. patent application GB 2,019,390 A.

12 The biocatalyst is a  
13 particulate fraction of the microorganisms, or an enzyme  
14 preparation derived therefrom. The microorganisms are  
15 cultivated in a nutrient medium furnishing oxygen and  
16 methane or dimethyl ether. The preferred microorganisms  
17 are obligative or facultative methylotrophs. The patent  
18 publication identifies several particularly preferred  
19 strains.

20 A process is disclosed for the microbiological  
21 production of ketones or secondary alcohols from  $C_3-C_6$   
22 alkanes, and ketones from  $C_3-C_6$  secondary alcohols, in  
23 U.K. patent application GB 2,018,772 A.

24 The process  
25 is conducted under aerobic conditions with resting micro-  
26 bial cells derived from a methylotrophic microorganism, or  
27 with an enzyme preparation derived from said cells. The  
28 microorganism has previously been grown under aerobic  
29 conditions in a nutrient medium containing a  $C_1$ -compound  
30 and energy source which is an inducer for the enzyme(s)  
31 responsible for producing the ketones. The compound is,  
32 for example, methane, methanol, dimethyl ether, methylamine,  
33 methyl formate, methyl carbonate, ethanol, propanol or  
34 butanol. The term microorganism includes bacteria, protozoa,  
35 yeasts and other. Yeast cells, grown as referred to, are  
36 illustrated in aerobically converting  $C_3-C_6$  secondary  
37 alcohols. Preparation, isolation and purification of a

1 novel C<sub>3</sub>-C<sub>6</sub> secondary alcohol dehydrogenase is also dis-  
2 closed.

3           The oxidation of alkanes having from 5 to 16 car-  
4 bon atoms, or of aliphatic alcohols having from 3 to 16  
5 carbon atoms, or of alkenes having from 3 to 8 carbon  
6 atoms, or cyclic organic compounds, utilizing a biocatalyst,  
7 is described in U.K. patent application GB 2,024,205 A.  
8

9           In the process described in this application,  
10 the biocatalyst may be a culture of a methane-utilizing  
11 bacterium of the species Methylosinus trichosporium or an  
12 extract thereof containing a methane oxidizing system.

13           Japanese Kokai 54-017184, published February 8,  
14 1979 to Dalton et al) assigned to National Research  
15 Development Corporation, describes the oxidation of  
16 straight chain alkanes having more than 3 and less than  
17 9 carbon atoms, of alkenes, and of cyclic organic compounds,  
18 utilizing as the biocatalyst a culture of a methane  
19 oxidizing bacterium or an extract thereof containing a  
20 methane oxidizing system. One way of carrying out the  
21 process involves immobilizing the cells on a suitable  
22 support material such as glass beads or a gel matrix, to  
23 form an immobilized enzyme preparation based on the use of  
24 cells as the enzyme source. The immobilized enzyme pre-  
25 paration is maintained in a packed or fluidized bed, and  
26 the gaseous substrate is passed through the bed. One of  
27 the claimed advantages of this process, when enzyme ex-  
28 tracts rather than whole cells were used, is said to be  
29 the regeneration in situ of cofactors or other biochemical  
30 species required for the enzymatic reaction. The dis-  
31 closure of this patent application is also incorporated  
32 herein by reference.  
33

34           An early disclosure of the conversion of  
35 hydrocarbons of the paraffinic type by bacterial action is  
36 described in U.S. patent 2,396,900. The method described  
37 in that patent converts normally gaseous paraffinic

1 hydrocarbons into heavy, waxy, oxygenated organic compounds  
2 by contacting the hydrocarbons in the presence of oxygen,  
3 with an aqueous nutrient solution inoculated with hydro-  
4 carbon consuming bacteria of the group consisting of  
5 Bacillus methanicus and Bacillus ethanicus. The patent  
6 describes a continuous process carried out in a bubble cap  
7 tower. The patent speaks of the bacteria consuming the  
8 hydrocarbons. It describes what goes on in the patented  
9 process as the synthesis, from light hydrocarbons, of  
10 oxygenated organic compounds of the various molecular  
11 weights, from low boiling alcohols to waxy acids, esters  
12 and alcohols. When the reaction is permitted to proceed  
13 to completion, the product is a predominantly heavy waxy  
14 body composed of fatty acids and esters thereof. It may  
15 be readily saponified.

16 A later U.S. patent, 3,622,465, describes a  
17 process in which the microorganism Arthrobacter simplex  
18 utilizes C<sub>3</sub>-C<sub>18</sub> straight chain hydrocarbons as a principal  
19 source of assimilable carbon and energy to produce single  
20 cell protein. The fermentation is carried out, in one  
21 embodiment of the invention, on a continuous basis in a  
22 sieve plate column, using liquified propane gas as the  
23 hydrocarbon.

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37 The present invention resides in one preferred

BAD ORIGINAL



1 embodiment in a continuous process that increases the  
2 oxidative state of an oxidizable organic substrate, com-  
3 prising establishing a series of separate but intercon-  
4 nected sequential contact zones, flowing a liquid com-  
5 position comprising a biocatalyst through each of said  
6 zones successively from a liquid inlet zone to a liquid  
7 outlet zone, flowing an oxidizing gas through each of  
8 said zones successively from a gas inlet zone to a gas  
9 outlet zone, in intimate, countercurrent contact with the  
10 flowing liquid in each of said zones, flowing an organic  
11 substrate successively through each of said zones in inti-  
12 mate, reactive contact with said gas and with the liquid  
13 composition containing said biocatalyst, and recovering  
14 liquid effluent discharged from the liquid outlet zone  
15 and gas effluent discharged from the gas outlet zone, the  
16 recovered effluents comprising at least some of the  
17 oxidizable organic substrate converted to a more advanced  
18 state of oxidization.

19 In this preferred embodiment, the gas-liquid con-  
20 tact apparatus in which the process is carried out is a  
21 bubble cap tower. In a very preferred mode of practice  
22 of the process,  $C_2-C_4$  n-alkenes and butadiene, particularly  
23 propylene, are converted to the corresponding epoxide.

24 The process of the invention is particularly  
25 useful for converting the gaseous alkanes and alkenes to  
26 their corresponding alcohols, aldehydes and acids, i.e.,  
27 for converting a  $C_2-C_4$  n-alkene, butadiene, or isobutylene,  
28 into the corresponding epoxide, such as, for example,  
29 ethylene oxide, propylene oxide, epoxy-butane, epoxy-butene,  
30 and epoxy-isobutane. The process can also be conducted to  
31 convert methane into methanol, formaldehyde, and formic  
32 acid. Gaseous alkanes can also be converted to the corres-  
33 ponding ketones, such as acetone, butanone-2, pentanone-2,  
34 and/or primary alcohols, such as ethanol, 1-propanol, 1-  
35 butanol, 1-pentanol, secondary alcohols, such as 2-propanol,  
36 2-butanol, 2-pentanol, and the like.

37 The process of the invention can also be practised

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1 for the oxidation of an organic compound ~~selected from~~  
2 ~~the group consisting of~~ <sup>which is</sup> an alkane having from 5 to 16  
3 carbon atoms inclusive, <sup>per molecule</sup> aliphatic alcohols (primary and  
4 secondary) having from 3 to 16 carbon atoms, <sup>per molecule</sup> an alkene  
5 having from 3 to 8 carbon atoms, <sup>per molecule or</sup> and a cyclic organic  
6 compound such as benzene or a phenol.

7 In the case of a liquid organic compound sub-  
8 strate, it can be introduced into the upper zone of the  
9 reactor, which preferably is a bubble cap tower, along  
10 with the liquid composition comprising the biocatalyst.

11 Also, by controlling process conditions, the  
12 process can be utilized for the production of biomass that  
13 is useful for the preparation of foodstuffs.

14 The microorganisms that are useful for producing  
15 enzymes for the practice of the invention, whether in  
16 whole cell form, or as a crude or purified enzyme, or  
17 otherwise, are the methylotrophs or methylophilic bacteria.  
18 These are a recognized genus of microbes.

19 The following description applies primarily to one embodiment  
20 of the invention, wherein the hydrocarbon feedstock is in the gaseous or  
21 vapour phase, and the equipment employed is a bubble cap tower.

22 In the drawing:

23 Figure 1 is a schematic flow diagram showing one way in which  
24 the process of the invention can be practised, making use of a bubble  
25 cap tower equipped with downspouts for liquid flow, the bubble cap tower  
26 being shown in a fragmentary vertical section, with only a few of the  
27 bubble caps being drawn in, and

28 Figure 2 is a fragmentary section, on an enlarged scale, showing  
29 in detail a preferred form of construction for an individual bubble cap  
30 for use in the practice of the invention.

31 Referring now in detail to the drawing a biocatalyst supply  
32 tank 10 is connected through a stub line 12 and a tee joint 14 to a  
33 supply line 16. The supply line 16 is connected through a fitting 18 to  
34 a liquid inlet line 20 that is capable of discharging liquid onto the  
35 uppermost tray 22 in a bubble cap tower 24.

36 The particular bubble cap tower configuration illustrated is  
37 one of older design and modest capacity. Each tray, like the uppermost  
tray 22, is equipped with a downtake pipe 26 of the conventional type,  
that serves to take overflow from the tray on which it is mounted, and  
carry it to the tray beneath. Each tray has mounted thereon a plurality  
of bubble caps 28.



1           Each bubble cap has a vapor nozzle 30 that is  
2 open at both of its ends and that is mounted so that its  
3 lower end communicates with the space below the under-  
4 surface of the tray. A holddown bolt 32 is disposed to  
5 project through a spider 34 that spaces the lower end of  
6 the bolt from the lower surface of the tray. The bolt 32  
7 projects upward through the vapor nozzle 30, and a  
8 second spider 36 is seated on the upper end of the  
9 vapor nozzle 30 about the bolt 32, to space the hood 38  
10 of the bubble cap from the vapor nozzle. The bolt 32  
11 projects through an opening in the hood 38 and a washer-  
12 nut assembly 40 is threaded on the upper end of the bolt  
13 32 to hold the bubble cap assembly together and secure  
14 it to the tray. Each cap is formed, in conventional  
15 fashion, with a plurality of vapor vents 42 about the lower  
16 portion of its hood.

17           In the modified bubble cap structure 28' shown  
18 in Fig. 2, the hood 38' is supported on and spaced from  
19 the vapor nozzle 30' by a sparger structure 41 that has  
20 sufficient structural strength to serve as a spacer but  
21 that has openings for the passage of gas or vapors there-  
22 through. The hood 38' is equipped with four legs 43 that  
23 space the hood 38' above the tray on which it is mounted,  
24 and support it.

25           As is customary, the downtake pipes 26 in  
26 successive trays are staggered from side to side, so that  
27 the direction of liquid flow is in one direction on one  
28 tray, and in the opposite direction on the next lower tray  
29 and so on.

30           A takeoff pipe 44 is mounted at the lower end  
31 of the bubble cap tower 24, positioned to carry off  
32 liquid from the lowermost tray. The lowermost tray 22'  
33 does not have a downtake pipe, so that the takeoff line 44  
34 provides the only discharge route from the tower for liquid.  
35 Some means, designated by the numeral 46 in Fig. 1, is  
36 connected to the line 44 to permit the separation of cells  
37 or other particulate form of enzyme preparation (when a

1 particulate form is used), from the product-containing  
2 liquid effluent. The separation device may be an ultra-  
3 filter, a centrifuge, hollow fibers, a conventional filter,  
4 or other appropriate device. Means (not shown) are  
5 provided to permit recycling of the separated cells or  
6 enzyme preparation, after-resuspension, dilution, or the  
7 like, as necessary, through a line 52 that is shown in the  
8 drawing as communicating with the separation means 46.  
9 The separation means 46 is also connected through a line  
10 48 with the product recovery unit 50, so that when the  
11 separating means 46 is a filter, for example, the fil-  
12 trate can be delivered through the line 48 into the  
13 product recovery unit 50.

14           The biocatalyst is recycled in toto, preferably.  
15 When its activity drops to less than about 30% to 50% of  
16 its original level, it is regenerated before being placed  
17 back in service. Regeneration is accomplished, in the  
18 case of whole cells, by growth on methane or its meta-  
19 bolites, or other appropriate substrate, as will be des-  
20 cribed in greater detail presently.

21           The separation means 46 is connected through a  
22 line 52 to the tee 14, so that the line 52 can be used as  
23 a recycle line.

24           The product recovery unit 50 may be, for  
25 example, a filter, a hydroclone, a centrifugal separator,  
26 or the like, depending upon the characteristics of the  
27 product or residue being fed to the product recovery unit.  
28 In any case, this unit 50 is provided with a means 54  
29 for removing product from the system, and with a line 56  
30 through which liquid can be pumped to a tank 58, for  
31 recycling. The tank 58 is preferably connected to a source  
32 of fresh buffer solution, and it should have sufficient  
33 capacity to accomodate the recycling liquid. Some  
34 agitation means (not shown) is preferably provided to  
35 insure homogeneity of the material in the tank. The tank  
36 58 is connected through a line 60 to the fitting 18, to  
37 permit material from the tank 58 to be fed through the

1 liquid in the line 20 to the upper tray 22 in the bubble  
2 cap tower.

3 In the vapor circulating system, a feed gas  
4 line 62 is provided that connects through a tee 64 and a  
5 stub line 66 with a generally conical space 68 at the  
6 bottom of the tower, beneath the lowermost tray 22'.

7 Feed gases, such as a mixture of gaseous hydro-  
8 carbons and oxygen or air, that are delivered through  
9 this system to the tower, then pass up through the tower  
10 in known fashion, and eventually collect in the generally  
11 conical space 70 at the upper end of the tower. These  
12 vapors are led off through a line 72 that connects the  
13 upper end of the tower with a product recovery unit 74.  
14 This unit is a conventional piece of equipment designed  
15 to separate the oxidized product from any residual un-  
16 reacted gaseous hydrocarbons, and oxygen or air. The  
17 product is led off through a line 76, and any residual  
18 unreacted substrate gas is recycled through a line 70 to  
19 a pump 80, from which it travels through a line 82 to the  
20 tee 64, for return to the bottom of the tower.

21 To practice the process of the invention, a  
22 mixture of feed gases, that is, gaseous hydrocarbons,  
23 and oxygen or air or other oxidizing gas, is introduced  
24 into the bottom of the reactor, which preferably is a  
25 bubble cap tower as shown. The gaseous mixture is passed  
26 through the reactor, and in the bubble cap tower, this  
27 means that it passes through the vapor nozzles of the  
28 individual bubble caps, making its way upward through  
29 the tower, tray by tray, in countercurrent contact with  
30 the liquid that is moving down through the tower. The  
31 bubbles are finely divided, and the individual bubble caps  
32 are positioned to allow the bubbles from each cap to  
33 collide with those from adjacent caps. Intimate contact  
34 is thus assured between the gaseous mixture, and the  
35 liquid on each tray. At the same time, the liquid is  
36 agitated by the bubbles that pass through it. At the top  
37 of the tower, residual gas passes off for further

1 processing and for possible recycling.

2 In the liquid cycle, a biocatalyst and buffer  
3 solution are fed into the top of the tower in a continuous  
4 stream. The liquid accumulates on the first tray until it  
5 overflows the downcomer pipe. It then makes its way down  
6 to the next lower tray, and so on, until it reaches the  
7 lowermost tray in the tower. It then passes out of the  
8 tower for further processing.

9 The role of the buffer solution is to maintain  
10 optimum conditions for the biocatalyst that is employed  
11 in the process. The liquid vehicle of the buffer solution  
12 also, depending upon the product formed and its  
13 characteristics, may collect to product. Alternatively,  
14 depending on the nature of the product and the reaction  
15 conditions, the product may pass off in the gas leaving the  
16 top of the reactor; or part may be in each effluent. The  
17 buffer solution also serves to supply energy or cofactors,  
18 if necessary, for the biocatalyst. Spent biocatalyst is  
19 separated out for recycling or for regeneration and re-  
20 use, or is collected for use in feed or for disposal.

21 In the processes with which the present invention  
22 is concerned, the operating temperature overall is  
23 generally kept in the range from ambient temperature to  
24 about 100°C, but preferably below about 75°C, depending  
25 on the vaporizing temperature of the substrate. Heat may  
26 be applied to the entire system or to selected parts of  
27 it, as desired, for temperature control, or heat exchange  
28 may be conducted for either heating or cooling as necessary.  
29 In addition, the reactor may be equipped to permit the  
30 addition of materials of any kind, as desired, at any tray  
31 level. In addition, for very large scale operations,  
32 high capacity bubble cap towers may be employed with over-  
33 flow weirs rather than downtake pipes, and with any  
34 desired arrangement for liquid flow on individual trays.

35 The effective concentration of the biocatalyst  
36 depends upon its activity, which tends to decrease over a  
37 period of time. Typically, when whole cells are employed,

1 the concentration will be in the range from about 1 mg/cc  
2 to about 100 mg/cc of cells in buffer solution, preferably  
3 from about 5 mg/cc to about 10 mg/cc. In a cell-free  
4 system, the concentration of enzyme may be in the range  
5 from about 0.1 mg/cc to about 100 mg/cc of purified or  
6 immobilized enzyme preparation in buffer solution.

7           The product may be recovered from the liquid  
8 discharge from the reactor by any convenient means  
9 appropriate, such as, for example, distillation, gas  
10 purging, and the like, depending upon the particular  
11 situation. A part or all of the product can also be  
12 recovered from the residual or exhaust gas taken from the  
13 top of the reactor. In this case, after stripping off  
14 any product present, the residual gas can be recycled by  
15 admixture with the incoming feed gases.

16           The size and capacity of the reactor selected  
17 will depend upon the desired scale of production and also  
18 on the solubility of the substrate hydrocarbons. A  
19 high bubble cap tower ordinarily will have a high partial  
20 pressure of the feed gasses and will benefit from higher  
21 solubility of the feed gases. The solubilities of the feed  
22 gases are usually the rate limiting factors of the  
23 reaction.

24           Substrate hydrocarbon gas or oxygen, oxygen-  
25 enriched air, or air can be injected at any desired level  
26 in the bubble cap tower to enrich the gas at that level.

27           For simplicity, Fig. 1 of the drawing shows only  
28 a single bubble cap tower. Although it is possible to use  
29 only a single tower it is preferred that two or more  
30 towers be used in series, with the fresh biocatalyst-buffer  
31 solution being directed into the tower from which the  
32 feed gas is finally discharging. That is, the fresh supply  
33 of feed gas is fed into the bottom of the tower from  
34 which the most spent biocatalyst-buffer mixture is being  
35 discharged. Thus, recycling of biocatalyst can be most  
36 carefully controlled as can be recycling of the effluent  
37 substrate gases. Preferably, the total residence time

1 for feed gas in the bubble cap tower should be at least  
2 one minute, and need not be more than 30 minutes, depending  
3 on the size of the bubble cap tower. The bubble cap  
4 tower installation can be designed accordingly.

5 The pressure differential required to transport  
6 the feed gases through a tower reactor system depends on  
7 the bubble cap design, depth of liquid per tray, number  
8 of trays per tower, and number of towers in use.

9 The biocatalyst that is employed in the reaction  
10 can be in the form of cells, enzyme solutions, or sus-  
11 pensions of immobilized cells or enzymes.

12 In the following description of preferred  
13 embodiments of the practice of the process, methane-  
14 induced methylotrophic microorganisms, or enzyme pre-  
15 parations derived therefrom, are used to increase the  
16 oxidative state of an oxidizable organic substrate, which  
17 is meant to include incorporating oxygen in an organic  
18 compound, as in epoxidizing olefins and converting alkanes  
19 to alcohols or ketones. In a preferred embodiment of  
20 the invention, the process is used to convert propylene  
21 to propylene oxide through the use of a biocatalyst.

22 The term "microorganism" is used herein in its  
23 broadest sense to include not only bacteria, but also  
24 yeasts, filamentous fungi, actinomycetes and protozoa, and  
25 especially the bacteria capable of oxidizing methane.

26 The term "enzyme preparation" is used to refer  
27 to any composition of matter than exhibits the desired  
28 oxygenase enzymatic activity. The term is used to refer,  
29 for example, to live whole cells, dried cells, cell ex-  
30 tracts, and refined and concentrated preparations derived  
31 from the cells. Enzyme preparations may be either in  
32 dry or liquid form. The term also includes the immobilized  
33 form of the enzyme, e.g., the whole cells of the methane  
34 grown microorganism, or enzyme extracts, immobilized or  
35 bound to an insoluble matrix by covalent chemical linkages,  
36 sorption, or entrapment of the enzyme within a gel lattice  
37 having pores large enough to allow the molecules of the

1 substrate and of the product to pass freely, but small  
2 enough to retain the enzyme.

3 The term "particulate fraction" refers to the  
4 oxygenase enzyme activity in the precipitated or sedi-  
5 mented material when the supernatant after centrifuging  
6 broken cells at 10,000 x g. for 30 minutes is centri-  
7 fugal for 1 hour at 40,000 x g. or greater.

8 In one preferred embodiment of the invention,  
9 practiced for oxidizing propylene to propylene oxide, the  
10 preferred biocatalyst is or is derived from, as an enzyme  
11 preparation, a methylotrophic organism of the kind  
12 referred to in GB 2,019,390 A, and identified as:  
13 Methylosinus trichosporium, Methylosinus sporium, Methylo-  
14 cystis parvus, Methylomonas methanica, Methylamonas albus,  
15 Methylomonas streptobacterium, Methylomonas agile,  
16 Methylomonas rubrum, Methylomonas rosaceus, Methylobacter  
17 chroococcum, Methylobacter bovis, Methylobacter capsulatus,  
18 Methylobacter vinelandii, Methylococcus capsulatus and  
19 Methylococcus capsulatus Strain Texas referred to by D. W.  
20 Ribbons, J. Bacteriol, 122, 1351-1363 (1975), and  
21 Methylococcus minimus. These methylotropic microorganisms  
22 may be used in the form of their whole cells, enzyme  
23 extracts thereof or immobilized preparations of those  
24 whole cells or enzyme extracts, such as by use of DEAE  
25 cellulose, on exchange resins, or porous alumina carriers,  
26 for example.

27 Subcultures of some of such suitable methylo-  
28 trophic microorganisms have been deposited with the  
29 official depository of the United States Department of  
30 Agriculture, Agriculture Research Service, Northern Regional  
31 Research Laboratory, Peoria, Illinois 61604, by depositing  
32 therein subcultures of each, and have received from the  
33 depository the individual NRRL strain designations as  
34 indicated below. These subcultures have been deposited in  
35 accordance with the procedures of the Department of  
36 Agriculture without any restriction, and progeny of these  
37 strains are available to the public, as follows:

1	2	USDA Agricultural Research Service	
3	<u>Culture</u>	<u>Designation</u>	<u>Strain</u>
4	<u>Methylosinus trichosporium</u>	NRRL B-11,196	A
5	<u>Methylosinus sporium</u>	NRRL B-11,197	B
6	<u>Methylocystis parvus</u>	NRRL B-11,198	C
7	<u>Methylomonas methanica</u>	NRRL B-11,199	D
8	<u>Methylomonas albus</u>	NRRL B-11,200	E
9	<u>Methylobacter capsulatus</u>	NRRL B-11,201	F

10           Typically, to grow the methylotrophic micro-  
11 organism and to induce the oxygenase or epoxidation enzyme  
12 system, the microorganisms are inoculated into a medium  
13 which is contacted with a gas mixture containing methane  
14 and oxygen. Methane may be supplied in the form of  
15 natural gas. For continuous flow culture the microorgan-  
16 isms may be grown in any suitably adapted fermentation  
17 vessel, for example, a stirred baffled fermentor or  
18 sparged tower fermentor, which is provided either with  
19 internal cooling or an external recycle cooling loop.  
20 Alternatively, the process of the present invention may be  
21 practised primarily for cell production, as will be  
22 described hereafter.

23           For continuous flow culture in a stirred, baffled  
24 fermentor, fresh medium may be continuously pumped into  
25 the culture at rates equivalent to 0.02 to 1 culture volume  
26 per hour and the culture may be removed at a rate such  
27 that the volume of culture remains constant. A gas  
28 mixture containing methane and oxygen and possibly carbon  
29 dioxide and other gases is contacted with the medium  
30 preferably by bubbling continuously through a sparger  
31 at the base of the vessel. The source of oxygen for the  
32 culture may be air, oxygen or oxygen-enriched air. Spent  
33 gas may be removed from the head of the vessel. The  
34 spent gas may be recycled either through an external loop  
35 or internally by means of a gas inducer impeller. The  
36 gas flows and recycle should be arranged to give maximum  
37 growth of microorganism and maximum utilization of methane.



1           The oxygenase enzyme system may be obtained as  
2 a crude extract, or as a cell-free particulate fraction,  
3 i.e., the material which precipitates or sediments when  
4 the supernatant, after centrifuging broken cells at  
5 10,000 x g for 30 mins., is centrifuged for 1 hour at  
6 10,000 x g or greater.

7           The microbial cells may be harvested from the  
8 growth medium by any of the standard techniques commonly  
9 used, for example, flocculation, sedimentation, and/or  
10 precipitation, followed by centrifugation and/or filtration.  
11 The biomass may also be dried, e.g., by freeze or spray  
12 drying and may be used in this form for further use in the  
13 epoxidation reaction. When using the cell-free enzyme,  
14 NADH and a metal (e.g., copper or iron), may be added to  
15 enhance the enzyme activity.

16           The following Examples demonstrate biocatalytic  
17 oxidation and biomass production in accordance with the  
18 invention. Throughout this application, all parts and  
19 percentages are by weight and all temperatures are in  
20 degrees Celsius, unless expressly stated to be otherwise.

## 21 Oxidation of Hydrocarbons

### 22 Example 1

#### 23 Oxidation of Propylene

24           A washed cell suspension of the microorganism  
25 Methylosinus trichosporium, NRRL B-11,196, hereafter  
26 referred to as Strain A, is placed in the biocatalyst  
27 supply tank 10. A supply of 0.05M potassium or sodium  
28 phosphate buffer solution, pH 7.0, is placed in the tank  
29 58. The valving (not shown) is adjusted so that a  
30 mixture of the buffer solution and cell suspension is  
31 circulated into the bubble cap tower 24, onto the surface  
32 of the uppermost tray 22. Circulation is continued until  
33 every tray is filled to capacity, and the liquid from the  
34 lowermost tray begins draining out of the tower. The  
35 valving is then arranged for complete recycling of the  
36 liquid containing the cell suspension. The cell concen-  
37 tration in the cell suspension is maintained at 5-10 mg/cc.

1           A mixture of gaseous propylene and oxygen-  
2 enriched air is pumped into the bottom of the bubble cap  
3 tower. The mole ratio of hydrocarbon gas to total oxygen  
4 is from about 1:1 to about 1:2. After a short interval of  
5 venting of the tower to permit purging the tower of its  
6 normal supply of air, the valving is arranged to direct  
7 vented gas to flow from the tower through the line 72,  
8 into the product recovery unit 74. Initially there is  
9 100% recycling of the gas for a short period of time, to  
10 permit the tower to equilibrate.

11           The tower heat exchange system (not shown) is  
12 adjusted to maintain the discharging liquid at about 30°-  
13 35°C. After a short time, equilibration quickly is  
14 achieved, and the valving is again adjusted so that the  
15 liquid from the bottom of the tower is delivered to the  
16 product recovery unit 50.

17           Under these operating conditions, the bulk of  
18 the propylene oxide product dissolves in the aqueous  
19 vehicle and is carried out of the tower through the line 44  
20 into the product recovery unit 50. It can be simply  
21 recovered in that unit by heating the water to drive off  
22 the propylene oxide. The water (buffer solution)  
23 preferably is then recycled for further use.

24           Some of the propylene oxide, however, remains  
25 in vapor form, and is discharged from the tower at its  
26 upper end. It can easily be recovered from the exhaust  
27 gases by chilling them to the point where the propylene  
28 oxide condenses as a liquid, and thus separates out  
29 readily from the other gases.

30           Other microorganism strains that may be used gen-  
31 erate whole cells for use in the cell suspension biocatalyst  
32 in the practice of the invention to produce propylene  
33 oxide include the following:

- 17 -

TABLE 1

Strain	Suitable Microorganism Strains
B	<u>Methylosinus sporium</u> (NRRL B-11,197)
C	<u>Methylosinus parvus</u> (NRRL B-11,198)
D	<u>Methylomonas methanica</u> (NRRL B-11,199)
E	<u>Methylomonas albus</u> (NRRL B-11,200)
F	<u>Methylobacter capsulatus</u> (NRRL B-11,201)
G	<u>Methylobacterium organophilum</u> (ATCC 24,886)
H	<u>Methylococcus capsulatus</u> (Texas) (ATCC 19,069)
I	<u>Methylococcus capsulatus</u> (Bath) (NCIB 11,132)

In similar fashion, strains A and B can be useful in the form of whole cell biocatalysts for the conversion of ethylene to ethylene oxide; butene-1 to 1-epoxy-butane; and butadiene to 1,2-epoxy-butene. Strain A is believed to effect more rapid conversions, under the stated conditions, with equal weights of cells in the biocatalyst carrier liquid, than Strain B, for the conversion of ethylene to ethylene oxide, propylene to propylene oxide; and butadiene to 1,2-epoxybutene. However, Strain B is believed to effect a more rapid conversion of butene-1 to 1,2-epoxy butane, than Strain A.

Both whole cells and cell-free extracts containing the oxygenase enzyme activity may be used in the epoxidation reaction. NADH and metal ion (iron or copper) may be added to enhance activity when the cell-free or purified enzyme preparations are employed.

Cell-free enzyme preparations may be prepared by disintegrating cells in an aqueous suspension, at 4°C, by a single passage through a French pressure cell at 15,000 psi, followed by centrifuging at 5,000 x g for 15 minutes to remove unbroken cells. The supernatant solution is then centrifuged at 40,000 x g for 30 minutes, yielding P (40) and soluble S(40) fractions. The S(40) fraction is subsequently centrifuged at 80,000 x g for 60 minutes, yielding particulate P(80) and soluble S(80) fractions. The two particulate fractions P(40) and P(80) are suspended in 25 mM potassium phosphate buffer,

1 pH 7.0, containing 5 mM magnesium chloride, and then are  
2 homogenized at 4°C for use. NADH is necessary for energy  
3 in cell-free extracts for optimum oxidation of alkenes.  
4 NAD is useful for oxidation of secondary alcohols.

5           In general, the epoxidation of a C<sub>2</sub>-C<sub>4</sub> n-alkene,  
6 lower dienes, or iso-alkenes, selected from the group  
7 consisting of ethylene, propylene, butene-1, butadiene,  
8 isobutylene, or isoprene, can be carried out where the  
9 microorganism, from which the biocatalyst is prepared,  
10 belongs to one of the genera Methylosinus, Methylocystis,  
11 Methylyomonas, Methylobacter, Methylococcus or Methylobac-  
12 terium. The preferred species are selected from  
13           Methylosinus trichosporium,  
14 Methylosinus sporium, Methylocystis parvus, Methylomonas  
15 methanica, Methylomonas albus, Methylomonas streptobactrium,  
16 Methylomonas agile, Methylomonas rubrum, Methylomonas  
17 rosaceus, Methylobacter chroocuccum, Methylobacter bovis,  
18 Methylobacter vinelandii, Methylococcus capsulatus,  
19 Methylococcus minimus and Methylobacterium organophilum.

20           The most preferred strains of microorganisms,  
21 for producing the biocatalyst, are those selected from ~~the~~  
22 ~~group consisting of~~ Strains A to I, above.

23           When the P(40) and P(80) fractions, prepared as  
24 described above, of the microorganisms identified below in  
25 Table II, are utilized in the process of Example 1, by  
26 substituting the particulate cell fraction for the whole  
27 cell suspension, a much more concentrated, and thus more  
28 highly active, biocatalyst action is available. However,  
29 the P(40) fraction contains most of the activity promoting  
30 propylene oxidation; the P(80) fraction contains some  
31 activity. While most of the enzyme activity appears in  
32 the P(40) fraction, on a weight basis, the activity in the  
33 P(80) fraction is almost as effective.

TABLE II

CELL-FREE PARTICULATE FRACTIONS OF RESTING MICROBIAL  
CELLS EFFECTIVE FOR THE PRODUCTION OF PROPYLENE OXIDE

<u>Strain</u>	<u>Microorganism</u>
<u>Type I Obligate Methylophils:</u>	
J	<u>Methylomonas streptobacterium</u> (NRRL B-11,208)
H	<u>Methylococcus capsulatus</u> (Texas, ATCC 19,069)
<u>Type II Obligate Methylophils:</u>	
K	<u>Methylosinus trichosporium</u> (NRRL B-11,202)
A	<u>Methylosinus trichosporium</u> (NRRL B-11,196)
<u>Facultative Methylophil:</u>	
L	<u>Methylobacterium sp.</u> (NRRL B-11,222)

Example 2

Oxidation of Methane

When the procedure of Example 1 is generally followed, but with the substitution of either methane or natural gas for propylene as the feed gas, the methane is readily hydroxylated to produce methanol, utilizing whole cell suspensions of microorganisms of the genera, species, and strains identified in Example 1.

In addition to cell suspensions, cell-free particulate fractions of resting microbial cells are effective for the production of methanol from methane. Thus, the P(40) and P(80) fractions can be produced from the microorganisms identified in Table II above, and these are effective in converting methane to methanol. On a weight for weight basis, the P(80) fraction is almost as effective as the P(40) fraction, generally.

General Comments on the Oxidation  
of C<sub>1</sub>-C<sub>4</sub> n-alkanes and n-alkenes

Three distinct groups of methane-utilizing organisms are demonstrated to be effective for the oxidation of C<sub>1</sub>-C<sub>4</sub> n-alkanes, and C<sub>2</sub>-C<sub>4</sub> alkenes, utilizing either cell suspensions or cell-free systems.

1 Thus, when, following the procedure of Example 1, the  
2 biocatalyst is made up from the P(40) particulate fraction  
3 of the microorganism strain identified in Table II as  
4 Strain K, ethylene is converted to ethylene oxide;  
5 propylene is converted to propylene oxide; 1-butene is  
6 converted to epoxy butane; butadiene is converted to  
7 epoxy butene; isobutylene is converted to epoxy isobutane;  
8 methane is converted to methanol; and ethane is converted  
9 to ethanol.

10 The optimum pH for the oxidation of methane to  
11 methanol is about pH 7.0, and the optimum temperature is  
12 about 30°C-40°C.

13 Since the methane mono-oxygenase from methane-  
14 utilizing bacteria appears to be a copper-containing or  
15 iron-containing protein, generally the rate of conversion  
16 of methane to methanol and of propylene to propylene oxide  
17 is increased by the addition of either a copper salt or  
18 an iron salt or both. The metal salts are generally  
19 added to the buffer solution but may be added to the  
20 biocatalyst supply, or to both. Only a very low concen-  
21 tration of metal ion is required, so that buildup should  
22 be avoided.

23 Similarly, the effectiveness of a cell-free  
24 fraction of Methylococcus capsulatus (CRL M1, NRRL B-11,219),  
25 hereafter Strain M, is found to increase the conversion  
26 of methane to methanol and the conversion of propylene to  
27 propylene oxide. The cell-free fraction of Strain L is  
28 produced by disrupting the cells in a French press  
29 following the procedure described earlier.

30 Generally for the conversion of propylene to prop-  
31 ylene oxide by cell suspension, the optimum pH range is from  
32 about 6 to about 7, and the optimum temperature is about  
33 30°C-40°C. Although the temperature may be in the range  
34 from ambient temperature to about 50°C, it is preferred  
35 that the temperature not be above about 40°C, since there  
36 is an apparent decrease in oxidation above 40°C, which may  
37 be attributable to enzyme instability or to the 35°C

- 21 -

1 boiling point of propylene oxide.

2           These reactions are inhibited by several metal-  
3 binding or metal-chelating agents. Consequently, the  
4 presence of such materials should be avoided. Such  
5 materials include, for example, 1,10-phenanthroline; alpha,  
6 alpha-bipyridyl potassium cyanide, thiosemicarbazide;  
7 thiourea, and 8-hydroxy quinoline.

8           In addition to the microorganisms mentioned  
9 above, the biocatalyst for the reactions described in  
10 Examples 1 and 2 may be derived from the organisms  
11 Methylococcus capsulatus (Bath), Strain I. Biocatalysts  
12 derived from this microorganism demonstrate some  
13 resistance to inhibition by metal-binding agents.

14. Increasing the Oxidative State of Oxidized Substrates as  
15 Well as of Hydrocarbons

---

16           The C<sub>3</sub>-C<sub>6</sub> methyl ketones, such as, for example,  
17 acetone and 2-butanone, can be prepared by the process of  
18 the invention, by utilizing as the feed gas a C<sub>3</sub>-C<sub>6</sub> alkane  
19 or a C<sub>3</sub>-C<sub>6</sub> secondary alcohol. The biocatalyst can consist  
20 of resting microbial cells or an enzyme preparation  
21 derived therefrom. The cells are derived from obligate  
22 or facultative methylotrophic microorganisms cultivated  
23 under aerobic conditions in a mineral-nutrient medium  
24 containing an oxygenase and/or dehydrogenase enzyme inducer  
25 as the growth and energy source. Example of such inducers  
26 include methane, in the case of methane-utilizing  
27 methylotrophic microorganisms, and methanol, dimethyl  
28 ether, methylamine, methylformate, methylcarbonate,  
29 ethanol, propanol, butanol, and the like.

30           For converting the C<sub>3</sub>-C<sub>6</sub> alkanes to the  
31 corresponding alcohols, aldehydes, and/or ketones, the  
32 microbial cells, or the enzyme preparations derived from  
33 the cells, may be derived from obligate or facultative  
34 methane-utilizing type methylotrophic microorganisms, but  
35 not the methanol-utilizing type. However, to convert the  
36 C<sub>3</sub>-C<sub>6</sub> secondary alcohols to the corresponding ketones, the  
37 microbial cells or the enzyme preparations derived from

1 the cells may be derived from either the obligate or  
2 facultative methane-utilizing or methanol-utilizing type  
3 methylotrophic microorganisms; or they may be derived from  
4 methylotrophic yeast strains aerobically grown on a  
5 plurality of methyl radical-donating compounds such as  
6 methanol, methyl amine, methyl formate, methyl carbonate,  
7 dimethyl ether, and the like.

8 Further, for oxidizing the C<sub>3</sub>-C<sub>6</sub> secondary  
9 alcohols to their corresponding methyl ketones, the enzyme  
10 employed may be an NAD-dependent secondary alcohol  
11 dehydrogenase, preferably in the form of a cell-free  
12 extract obtained from bacteria or yeast grown on methanol.

13 The use of whole cells is particularly suitable  
14 for the oxidation of the lower molecular weight and/or  
15 more lipophilic substrates which may be advantageously  
16 absorbed through the cell membrane. In relation to the  
17 use of thermophilic methane-oxidizing bacteria such as  
18 M. capsulatus, the use of whole cells is particularly  
19 advantageous in view of the high growth temperatures  
20 e.g., an optimum growth temperature of 45°C for M.  
21 capsulatus (Bath), Strain I above, which may be  
22 tolerated by the organisms, thus conveniently diminishing  
23 cooling requirements.

24 As an alternative to the use of whole cells,  
25 appropriate enzyme extracts of methane-oxidizing bacteria  
26 may be used, and may be either membrane associated or  
27 soluble extracts. Preferably soluble enzyme extracts,  
28 such as those obtained from the Bath strain of M. capsul-  
29 atus, Strain I, for instance by centrifugation of  
30 crude cell extracts, may be employed. Substrates may be  
31 oxidized by direct interaction with a solution or  
32 suspension of extracts, or more preferably the extracts  
33 are first immobilized by attachment to or within a  
34 suitable solid phase material, such as glass, cellulose  
35 or a synthetic polymeric material, which is contacted with  
36 the substrate. The use of extracts is generally applicable  
37 to the oxidation of all substrates included within the



1 scope of the invention, though it will be appreciated,  
2 however, that when extracts are used the co-factor NADH  
3 is usually required for oxidation to proceed.

4         Processes according to the invention employing  
5 enzyme extracts typically comprise as an essential  
6 feature the supply, or preferably the regeneration, of  
7 co-factors or other biochemical species required or  
8 useful in the enzymatic reaction. Any suitable method  
9 or means may be employed for regeneration of these bio-  
10 chemical species. For instance, with crude enzyme pre-  
11 parations, formate or formaldehyde, or other suitable  
12 electron donor material, together with a catalytic amount  
13 of NAD may be used to regenerate NADH for the enzymatic  
14 reaction. Catalytic quantities of other required bio-  
15 chemical species may be regenerated similarly.

16         For a given substrate the rate of oxidation  
17 and products obtained may vary having regard to the  
18 type of oxidizing agent used e.g., enzyme extract or  
19 whole cells, the species of organism and conditions  
20 employed during the oxidation process, and the rate of  
21 oxidation and products may be optimized as required.  
22 Optimum organisms and conditions may be determined by  
23 simple experiments which will be apparent to workers  
24 skilled in the art, e.g., similar to those described  
25 hereinafter in the specific examples. For example, in  
26 the oxidation of propene using whole organism of various  
27 methane-oxidizing bacteria, organisms of the genus  
28 Methylomonas, especially M. albus, have been found to  
29 exhibit particularly desirable specific activities for  
30 oxidation of the propene to 1,2-epoxypropane.

31         In one specific embodiment of the present inven-  
32 tion, the process of the invention is practised to bring  
33 either a C<sub>3</sub>-C<sub>6</sub> alkane or a C<sub>3</sub>-C<sub>6</sub> secondary alcohol into  
34 contact, under oxidizing conditions, with resting  
35 microbial cells derived from obligate or facultative  
36 methylotrophic organisms or enzyme preparations derived  
37 from these cells, where the microorganisms have been

1 previously grown under aerobic conditions in a nutrient  
2 medium containing methane. The conversion oxidizes the  
3 C<sub>3</sub>-C<sub>6</sub> alkanes to alcohols and oxidizes C<sub>3</sub>-C<sub>6</sub> secondary  
4 alcohols to C<sub>3</sub>-C<sub>6</sub> methyl ketones. The microorganisms  
5 may have been grown under aerobic conditions in a  
6 nutrient medium containing methanol, for the conversion  
7 of secondary alcohols to the methyl ketones.

8 The C<sub>3</sub>-C<sub>6</sub> alkanes used in the practice of the  
9 invention are preferably linear n-alkanes such as, for  
10 example, propane, n-butane, n-pentane, and n-hexane.  
11 The C<sub>3</sub>-C<sub>6</sub> secondary alcohols are preferably derived from  
12 linear C<sub>3</sub>-C<sub>6</sub> alkanes, most preferably, 2-propanol and  
13 2-butanol.

14 A preferred group of methane-utilizing methyl-  
15 otrophic microorganisms includes those microorganisms  
16 derived from the genera: Methylosinus, Methylocystis,  
17 Methylomonas, Methylobacter, Methylococcus and  
18 Methylobacterium.

19 Preferred group of methanol-utilizing methylo-  
20 trophic microorganisms include those microorganisms de-  
21 rived from the genera: Methanomonas; Pseudomonas;  
22 Bacterium; Hyphomicrobium; Achromobacter; Protaminobacter;  
23 Vibrio; Rhodopseudomonas; Bacillus; Brevibacterium;  
24 Candida; and Hansenula.

25 Methylotrophic microorganisms species that may  
26 be employed include Methylosinus trichosporium, Methylo-  
27 sinus sporium, Methylocystis parvus, Methylomonas  
28 methanica, Methylomonas albus, Methylomonas streptobac-  
29 terium, Methylomonas agile, Methylomonas rubrum, Methyl-  
30 omonas rosaceus, Methylobacter chroococum, Methylobacter  
31 bovis, Methylobacter capsulatus, Methylobacter vinelandii,  
32 Methylococcus capsulatus (including Methylococcus  
33 capsulatus Strain Bath referred to by J. Colby and H.  
34 Dalton, J. Biochem., 157 495-497 (1976)), Methylococcus  
35 capsulatus Strain Texas referred to by D. W. Ribbons, J.  
36 Bacteroil, 122 1351-1363 (1975)), and Methylococcus  
37 minimus. These methylotrophic microorganisms may be used

1 in the form of their whole cells, enzyme extracts  
2 thereof, or immobilized preparations of those whole cells  
3 or enzyme extracts, such as those prepared by the use of  
4 DEAE cellulose, an ion exchange resin, or porous alumina,  
5 as carriers.

6 Publicly available subcultures of the species  
7 are identified above in Table I. In addition, the  
8 following yeasts may be used in the practice of the  
9 invention:

TABLE III

Strain	Strain Name	U.S.D.A. Agriculture Research Center and Designation
N	<u>Pichia</u> sp.	NRRL Y-11,328
O	<u>Torulopsis</u> sp.	NRRL Y-11,419
P	<u>Klockera</u> sp.	NRRL Y-11,420

17 In addition, the bacterial strains disclosed in  
18 Belgian Patent No. 875,512

19  
20 may be used to practise the invention.  
21 Typical bacterial strains that are disclosed in this  
22 patent are identified as follows:

TABLE IV

Strain	Name	U.S.D.A. Agriculture Research Center and Designation
K	<u>Methylosinus</u> <u>trichosporium</u>	NRRL B-11,202
J	<u>Methylomonas</u> <u>streptobacterium</u>	NRRL B-11,208
Q	<u>Methylomonas</u> <u>agile</u>	NRRL B-11,209
R	<u>Methylococcus</u> <u>capsulatus</u>	NRRL B-11,219
S	<u>Methylobacterium</u> <u>organophilum</u>	NRRL B-11,222

1 Example 32 Conversion of Propane to Acetone

3 A whole cell suspension of Methylomonas albus  
4 (NRRL B-11,200), identified above as Strain E, is used as  
5 the biocatalyst and is circulated with a 0.05M phosphate,  
6 pH 7.0, buffer solution through a bubble cap tower in  
7 the manner described in Example 1. The feed gas mixture  
8 is made up of propane and oxygen-enriched air. The  
9 temperature of the tower is maintained at about 35°C.

10 Most of the acetone product, being infinitely  
11 soluble in water and having a boiling point of about 56.5°C,  
12 leaves the tower in the liquid discharging from the lower-  
13 most tray. The acetone product can be separated from the  
14 water by a conventional solvent recovery technique, in  
15 the product recovery unit. A very small amount of acetone  
16 appears in the gaseous discharge from the bubble cap  
17 tower, from which it may be recovered by a combination of  
18 recycling and washing of the effluent gases.

19 Similarly, the cell suspensions of the  
20 following microorganisms, grown on methane, are useful in  
21 the practice of the process of the invention, for  
22 converting not only propane to acetone, but also n-butane  
23 to 2-butanone, n-pentane to 2-pentanone, and n-hexane to  
24 2-hexanone:

25 TABLE V

26 Methylotrophic Microorganism Strain Identification, Whose  
27 Resting Cell Suspensions are Useful for the Oxidation of  
28 Hydrocarbons to Ketones

29 Strain

30 A	<u>Methylosinus trichosporium</u> (NRRL B-11,196)
31 C	<u>Methylocystis parvus</u> (NRRL B-11,198)
32 D	<u>Methylomonas methanica</u> (NRRL B-11,199)
33 F	<u>Methylobacter capsulatus</u> (NRRL B-11,201)
34 H	<u>Methylococcus capsulatus</u> Texas (ATTC 19,069)
35 T	<u>Methylobacterium organophilum</u> (ATCC 24,886)

36 In addition, Strain E can be demonstrated to be  
37 useful for the conversion of n-butane to 2-butanone.

1 Similarly, Strain B can be demonstrated to be useful  
2 for the conversion of n-propane to acetone, and for the  
3 conversion of n-butane to 2-butanone.

#### 4 Example 4

#### 5 Conversion of Secondary Alcohols to Ketones

6           Following the procedure of the invention, but  
7 modified from the procedure of Example 1 in view of the  
8 higher boiling point of the substrate, and utilizing a  
9 bubble cap tower as a contact device, suspensions of  
10 resting cells of the methylotrophic microorganisms of  
11 Table V can be demonstrated to be useful for the con-  
12 version of 2-propanol to acetone, 2-butanol to 2-butanone,  
13 2-pentanol to 2-pentanone, and 2-hexanol to 2-hexanone.  
14 The substrate secondary alcohol in its liquid form is  
15 supplied as a continuous stream to the top tray of the  
16 tower. Generally the product ketone, which is also of  
17 relatively high boiling point, is taken off in liquid form  
18 from the lower end of the tower.

19           To produce the biocatalysts that are useful  
20 for this conversion, methane-utilizing methylotrophic  
21 microorganisms are each aerobically grown in a methanol-  
22 containing nutrient medium instead of methane-containing  
23 medium.

24           After growth of any particular microorganism on  
25 a suitable nutrient medium containing methanol as the  
26 alcohol dehydrogenase inducer and major source of carbon  
27 and energy for growth, the cells are harvested and washed.  
28 The cells are harvested by centrifugation at 10,000 x g at  
29 4°C for 30 min. The cell pellet is washed twice with a  
30 0.05 M phosphate buffer at a pH of about 7.0, containing  
31 0.02 M magnesium chloride. The washed cells are then  
32 suspended in a phosphate buffer at 0.05 M phosphate buffer  
33 at pH 7.0.

34           The resting cell suspensions of the strains  
35 identified in Table V are also operative if grown on  
36 methane. Similarly, Strains B and E can be demonstrated  
37 to be useful for the oxidation of 2-propanol to acetone

1 and of 2-butanol to 2-butanone. In each case, it is  
2 useful to have the resting cell suspensions suspended in  
3 a 0.05 M phosphate buffer at a pH of about 7.0.

4 In an exemplary demonstration of the invention,  
5 such a cell suspension (about 10 mg cells/ml) is  
6 prepared from cells of Strain E grown on methanol.  
7 Isopropanol is added continuously into the recycling  
8 liquid composition, to form a 50% isopropanol concen-  
9 tration solution on the uppermost tray. The tower  
10 temperature is maintained at about 40°C. Air is used as  
11 the feed gas.

12 The acetone product leaves the bubble cap tower  
13 with the liquid effluent. It can be separated from the  
14 residual substrate in the liquid effluent and recovered  
15 by conventional techniques, such as distillation.

16 Example 5

17 Biocatalytic Oxidation of Secondary Alcohols to Ketones

18 In this example, the biocatalyst once again  
19 is a suspension of resting microbial cells. The cells  
20 are those of methanol-utilizing methylotrophic micro-  
21 organisms, grown on methanol.

22 The procedure of the preceding example is  
23 repeated, with the obligate or facultative methanol-  
24 using methylotrophic microorganisms each aerobically  
25 grown in a methanol-containing nutrient medium. The  
26 nutrients in the medium include 0.4% V/V methanol, used  
27 as the alcohol dehydrogenase inducer and as the major  
28 carbon and energy source for growth. The cells are har-  
29 vested and washed as in the preceding example. The  
30 resting cells are then suspended in a buffer solution  
31 as in the preceding example, and are employed in the  
32 process of the invention.

TABLE VI

Identification of Strains Useful for the Conversion of  
Secondary Alcohols to Ketones by Cell-Suspensions of  
Methanol-Obligate and Facultative Methanol-Utilizing  
Methylotrophs

<u>Strain</u>	<u>Methylotrophic Microorganism Strain Identification</u>
U	<u>Pseudomonas</u> <u>sp.</u> (ATCC 25,262) (Facultative)
V	<u>Pseudomonas</u> <u>sp.</u> (ATCC 21,438) (Facultative)
W	<u>Pseudomonas</u> <u>sp.</u> (ATCC 21,439) (Obligate)
X	<u>Methanomonas</u> <u>methylovora</u> (ATCC 21,852) (Obligate)

In a modification of the practice of the invention, Strains T and V are each aerobically grown in an alcohol dehydrogenase-inducing growth medium containing methylamine or methylformate as the alcohol dehydrogenase enzyme inducer and growth substrate instead of methane, comprising 0.4 V/V of the growth substrate as the major carbon and energy source. The cells are harvested and washed as previously described, and suspended in a phosphate buffer for use. In both cases, the cell suspensions are effective for the conversion, in each case, of 2-propanol to acetone, of 2-butanol to 2-butanone, of 2-pentanol to 2-pentanone, and of 2-hexanol to 2-hexanone.

#### SUMMARY

#### Considerations Relating to the Conversion of Secondary Alcohols to Ketones With Cell Suspensions

The optimum pH for the production of ketones does not seem to be critical. The oxidation reaction goes forward at pH values in the range from about 5 to about 10, but generally, a pH of about 8.0 is preferred.

Cell concentration has a direct influence in the rate of conversion. Generally, an increase in conversion rate can be achieved by an increase in concentration of cells.

At least some metal chelating agents appear to exhibit an inhibitory effect on the conversion.

1 Both cell suspensions and cell-free extracts  
2 of  $C_1$ -compound grown yeasts enzymatically convert  $C_3$ - $C_6$   
3 secondary alcohols to the corresponding methyl ketones.  
4 Further, that cell suspensions of the yeasts: Candida  
5 utilis (ATCC 26,387); Hansenula polymorpha (ATCC 26,012);  
6 Pichia sp. (NRRL Y-11,328); Torulopsis sp. strain A  
7 (NRRL Y-11,419); and Kloeckera sp. strain A<sub>2</sub> (NRRL Y-11,420),  
8 grown on various  $C_1$  compounds (e.g., methanol, methylamine  
9 methyl formate), ethanol, and propylamine, can be used to  
10 catalyze the oxidation of  $C_3$ - $C_6$  secondary alcohols to  
11 the corresponding methyl ketones.

12 To derive purified SADH from a yeast, the cells  
13 are harvested during exponential growth by centrifugation  
14 at 12,000 x g for 15 min. The cell pellet is washed twice  
15 with 50 mM phosphate buffer, pH 7. The final pellet is  
16 resuspended in the same buffer. Cell suspensions of  
17 yeasts grown on ethanol, methylamine, and methylformate  
18 can be prepared as described above using 0.4 v/v ethanol,  
19 10 mM methylamine, and 10 mM methylformate, as the sole  
20 source of carbon and energy, for example.

21 The activity of purified yeast-derived SADH is  
22 inhibited by sulfhydryl inhibitors and metal-binding  
23 agents. The optimum pH of the purified enzyme is about  
24 8. The purified enzyme requires NAD as an electron  
25 acceptor.

#### 26 General: Conversion to Alcohols

27 Cell suspensions and cell-free particulate  
28 fractions of methane-grown methylotroph microorganisms are  
29 capable of catalyzing the conversion of lower alkanes to  
30 the corresponding alcohols, both primary and secondary.  
31 The conditions for preparing the cell suspensions or the  
32 cell-free particulate fractions from methane-grown methyl-  
33 otroph microorganisms are generally the same as described  
34 above. The cell-free particulate fraction requires the  
35 presence of NADH as an electron donor.

36 The conversion to the alcohol is inhibited by



1 metal-binding agents. Propylene also inhibits the  
2 conversion, which suggests that the propylene and n-alkane  
3 (e.g., propane) are competing for the same enzyme  
4 system(s). Ascorbate and reduced nicotinamide adenine  
5 dinucleotide phosphate (NADPH) can each be utilized as  
6 an electron donor in place of NADH for the conversion.

7 Cell suspensions of the following are useful  
8 for the conversion of n-alkanes to secondary alcohols,  
9 for example:

10 TABLE VII

11 Exemplary Microorganisms Grown on Methane, and  
12 Useful for the Conversion of N-Alkanes to Alcohols

13 <u>Strain</u>	<u>Microorganisms</u>
14 A	<u>Methylosinus trichosporium</u> (NRRL B-11)
15 H	<u>Methylococcus capsulatus</u> (Texas,
16	ATCC 19,609)
17 F	<u>Methylobacter capsulatus</u> (NRRL B-11,201)
18 K	<u>Methylosinus sp.</u> (NRRL B-11,202)
19 J	<u>Methylobacterium sp.</u> (NRRL B-11,208)
20 Q	<u>Methylomonas sp.</u> (NRRL B-11,209)

21 Example 6

23 Oxidation of 2-Butanol to 2-Butanone by Means of a Cell-  
24 Free Enzyme Preparation from a C<sub>1</sub>-Utilizing Microbe

25 The effectiveness of this biocatalytic demon-  
26 stration, utilizing cell-free soluble extracts, can be  
27 demonstrated with extracts derived from a plurality of  
28 different types of microbes. To prepare the cell-free  
29 secondary alcohol dehydrogenase (SADH) system, the washed  
30 cells are disrupted with a Wave Energy Ultrasonic Oscil-  
31 lator, Model W 201 (Wave Energy Systems, Inc., Newtown,  
32 Pa.) and are centrifuged at 20,000 x g for 30 mins. The  
33 clear supernatant contains the SADH activity.

34 All of the cell-free extracts require the  
35 addition of a co-factor, NAD, for activity. This appears  
36 to be a highly specific cofactor.

37 Cell-free extracts, useful in the practice of  
38 the invention described herein, can be used in the

1 practice of the process of the invention, when the  
 2 microbes are cultivated on the growth substrates identi-  
 3 fied respectively in Table VIII below:

4 TABLE VIII

5 C<sub>1</sub>-Utilizing Microorganisms Useful in the Oxidation of  
 6 2-Butanol to 2-Butanone by Cell-Free Soluble Extracts

7		Microbes	Growth
8	<u>Strain</u>	<u>Obligate Methylophils</u>	<u>Substrate</u>
9		<u>Type 1 membrane structure</u>	
10	A	<u>Methylosinus trichosporium</u>	CH <sub>4</sub>
11		(NRRL B-11,196)	CH <sub>3</sub> OH
12			CH <sub>3</sub> NH <sub>2</sub>
13			HCOOCH <sub>3</sub>
14	B	<u>Methylosinus sporium</u> (NRRL B-11,197)	CH <sub>4</sub>
15	C	<u>Methylocystis parvus</u> (NRRL B-11,198)	CH <sub>4</sub>
16		<u>Type 2 membrane structure</u>	
17	D	<u>Methylomonas methanica</u>	CH <sub>4</sub>
18		(NRRL B-11,199)	
19	E	<u>Methylomonas albus</u>	CH <sub>4</sub>
20		(NRRL B-11,200)	
21	J	<u>Methylomonas streptobacterium</u>	CH <sub>4</sub>
22		(NRRL B-11,208)	
23	Q	<u>Methylomonas agile</u>	CH <sub>4</sub>
24		(NRRL B-11,209)	
25	R	<u>Methylococcus capsulatus</u>	CH <sub>4</sub>
26		(NRRL B-11,219)	CH <sub>3</sub> OH
27			CH <sub>3</sub> NH <sub>2</sub>
28			HCOOCH <sub>3</sub>
29	F	<u>Methylococcus capsulatus</u>	CH <sub>4</sub>
30		(NRRL B-11,201)	
31		<u>Facultative methane-utilizers</u>	
32	L	<u>Methylobacterium organophilum</u>	CH <sub>4</sub>
33		(NRRL B-11,222)	CH <sub>3</sub> OH
34			CH <sub>3</sub> NH <sub>2</sub>
35			HCOOCH <sub>3</sub>
36	G	<u>Methylobacterium organophilum</u>	CH <sub>4</sub>
37		(ATCC 27,886)	

1	<u>TABLE VIII (continued)</u>		<u>Growth Substrate</u>
2	<u>Strain</u>	<u>Microbes</u>	
3		<u>Obligate Methanol-utilizer</u>	
4	W	<u>Pseudomonas sp.</u> (ATCC 21,439)	CH <sub>3</sub> OH
5			
6	X	<u>Methylomonas methylovora</u> (ATCC 21,852)	CH <sub>3</sub> OH
7			
8		<u>Facultative methanol-utilizers</u>	
9	V	<u>Pseudomonas sp.</u> (ATCC 21,438)	CH <sub>3</sub> OH
10			
11	U	<u>Pseudomonas Ms.</u> (ATCC 25,262)	CH <sub>3</sub> OH
12			
13		<u>Yeasts</u>	
14		<u>Candida utilis</u> (ATCC 26,387)	CH <sub>3</sub> OH
15			
16		<u>Hansenula polymorpha</u> (ATCC 26,102)	CH <sub>3</sub> OH CH <sub>3</sub> NH <sub>2</sub> HCOOCH <sub>3</sub>
17			
18		<u>Hansenula polymorpha</u> (NRRL Y-2214)	CH <sub>3</sub> OH
19			
20		<u>Hansenula polymorpha</u> (NRRL Y-2267)	CH <sub>3</sub> OH
21			
22		<u>Hansenula amonala</u> (NRRL Y-336)	CH <sub>3</sub> OH
23			
24		<u>Pichia pastoris</u> (NRRL Y-55)	CH <sub>3</sub> OH
25			
26		<u>Pichia pastoris</u> (NRRL Y-7556)	CH <sub>3</sub> OH
27			
28		<u>Pichia pastoris</u> (NRRL Y-7556)	CH <sub>3</sub> OH
29			

30 Generally, Strain B, cultured on methanol, is  
 31 observed to induce an extremely rapid reaction for the  
 32 conversion of 2-butanol to 2-butanone, compared to the  
 33 soluble crude extracts of the other C<sub>1</sub>-utilizers.

34 In carrying out the reaction, the amount of  
 35 the cofactor NAD that is consumed is substantial. The  
 36 molar consumption of NAD is very close to the moles of  
 37 2-butanol converted in the oxidation reaction to  
 38 2-butanone, for example.

1 Example 72 Biocatalytic Oxidation Using a Purified Enzyme

3 In the preceding example, the enzyme preparation  
4 described is a crude soluble, cell-free extract. In  
5 the present example, a purified secondary alcohol  
6 dehydrogenase (SADH) is used.

7 SADH from an obligate methanol utilizer,  
8 Pseudomonas sp. (ATCC 21,439), Strain W, is purified as  
9 follows. Cells grown on methanol as the carbon source  
10 are suspended in 0.05 M sodium phosphate buffer, at pH  
11 7.0, with 0.5 mM dithiothretol. The cells are then  
12 disrupted sonically, and a crude extract is separated by  
13 centrifugation.

14 The crude extract is heat treated at 50°C in a  
15 water bath for 10 mins. The resulting precipitate is  
16 removed by centrifugation. Protamine sulfate (2%  
17 solution in a 0.1 M Tris base) (Buffer A), is added to  
18 the supernatant solution with agitation.

19 After standing, the abstract is centrifuged.  
20 The supernatant solution is fractionated with solid  
21 ammonium sulfate. The material precipitating between  
22 30% and 60% saturation is collected, and dialyzed over-  
23 night against Buffer A.

24 The dialyzed material is applied to a DEAE  
25 cellulose column that has been equilibrated with Buffer A.  
26 The SADH activity is eluted. This DEAE cellulose eluate  
27 is concentrated by ammonium sulfate fractionation.  
28 Material precipitating between 30% and 50% ammonium  
29 sulfate saturation is collected by centrifugation and  
30 dialyzed overnight against Buffer A. This fraction is  
31 washed further and filtered through an Amicon unit with an  
32 XM 50 membrane. The concentrated fraction inside the  
33 Amicon unit is applied to an Affi-Gel Blue Column that  
34 has been equilibrated with Buffer A for affinity  
35 chromatography. The column is washed overnight with  
36 Buffer A and then is eluted with Buffer A containing 5mM  
37 NAD. The SADH activity is recovered in the eluate.

The purified SADH may be used directly for converting  $C_3$ - $C_6$  secondary alcohols to the corresponding methyl ketones, in the process of the present invention. A source of NAD must be added either to the biocatalyst or to the liquid stream that is being fed to the uppermost tray in the bubble cap tower.

The purification procedure described above may be modified by omitting the heat treatment, which results in higher specific activity.

In using the purified SADH, the optimum pH is from about 8 to about 9, and while the optimum temperature is in the range from about 30°C to about 35°C.

The substrate specificity of purified SADH is highest for 2-propanol and 2-butanol. However, it is effective in catalyzing the oxidation of 2-pentanol, 2-hexanol, acetadehyde, cyclohexanol, butane-1,3-diol, and butane-2,3-diol.

Particulate fractions of the following are exemplary of those methylotrophs useful for converting n-alkanes to alcohols:

TABLE IX

Hydroxylation of N-alkanes to Alcohols by  
Particulate P(40) Fraction of Methylotrophs

<u>Style</u>	<u>Organisms</u>
<u>Strain</u>	
K	<u>Methylosinus sp.</u> (NRRL B-11,202)
H	<u>Methylococcus capsulatus</u> (Texas, ATCC 19,069)
A	<u>Methylosinus trichosporium</u> (NRRL B-11,196)
S	<u>Methylobacterium sp.</u> (NRRL B-11,222)
a) Particulate P(40) fraction is prepared as follows: Cell-suspensions at 4°C are disintegrated through a French Pressure cell and centrifuged at 5,000 x g for 30 min. to remove unbroken bacteria. The supernatant solution is then centrifuged at 40,000 x g for 60 min. at 4°C, yielding the particulate P(40) and soluble S(40) fractions.	

The process of the invention is effective for oxidizing n-alkanes, although mixtures of oxidation

1 products are produced. Thus, when cell suspensions of  
2 methane-grown Strain A and Strain S, for example, are  
3 employed, the products are a plurality of oxidation pro-  
4 ducts including primary and secondary alcohols, methyl  
5 ketones and aldehydes, as shown below in Table X.

6 TABLE X

7 CONVERSION OF N-ALKANES TO OXIDATION PRODUCTS

8 Substrate on Which Strain A 9 or Strain S is Grown	Products
10 Methane	Methanol
11 Ethane	Ethanol
12 Propane	1-Propanol
13	2-Propanol
14	Propanol
15	Acetone
16 Butane	1-Butanol
17	2-Butanol
18	2-Butanone
19	n-butanol

20 Each enzyme preparation favors the production of  
21 one conversion product, generally, more than others. The  
22 rates can readily be determined by experimental practice  
23 of the process. Similarly, optimum temperatures and pH  
24 values are readily determinable for each particular  
25 reaction system.

26 Oxidation of Higher Molecular Weight Organic Compounds

27 The process of the invention can also be  
28 practised for the oxidation of an organic compound  
29 which is an alkane having from 5 to 16 carbon atoms inclusive  
30 per molecule, an aliphatic alcohol having from 3 to 16 carbon  
31 atoms per molecule, an alkene having from 3 to 8 carbon atoms  
32 per molecule or a cyclic organic compound such as benzene or a  
33 phenol.

34 Any of the microorganisms previously named,  
35 containing a methane oxidizing system, or an enzyme  
36 preparation derived therefrom, may be used as the bio-  
37 catalyst. Preferably, the biocatalyst is derived from a  
38 culture of methane-utilizing bacteria of the species

- 1 Methylylosinus trichosporium, most preferably,  
 2 Methylosinus trichosporium (NRRL B-11,196) Strain A.

### 3 Example 9

#### 4 Oxidation of Higher Molecular Weight Organic Compounds

5 The oxidations listed in Table XI below may be  
 6 performed utilizing a suspension of cells of Methylosinus  
 7 trichosporium (NRRL B-11,196), Strain A, cultured with  
 8 methane as a carbon source.

9 The cells can be harvested during the late  
 10 logarithmic phase (batch culture) or during the steady  
 11 state (continuous culture) by centrifuging at 5,000 g for  
 12 30 mins. The cells are then washed twice with 20 mM  
 13 sodium phosphate buffer (e.g. at pH 7.0) and, after  
 14 resuspending in the same buffer, they may be stored at a  
 15 lower temperature, i.e., 0°C or less, until required for  
 16 use.

17 For use in the process, the cells are suspended  
 18 in a 20 mM sodium phosphate buffer, pH 7.0, at 5-10 mg  
 19 cells per ml. The following conversions can be carried  
 20 out utilizing such cell-suspensions:

21 TABLE XI

#### 22 Oxidation of Higher Organic Compounds

23 <u>Conversion No.</u>	<u>Substrate</u>	<u>Oxidation Product(s)</u>
24 1	Benzene	Phenol
25 2	Benzyl alcohol	Benzaldehyde and p-
26		hydroxybenzyl alcohol
27 3	o-Cresol	5-methyl,1,3-benzene-
28		diol
29 4	Hexane	Hexan-1-ol
30 5	Hexadecane	Hexadecane-1-ol
31 6	Cyclohexane	Cyclohexanol and 3-
32		hydroxycyclohexanone
33 7	Cyclohexanol	3-hydroxycyclohexanone
34 8	Ethylbenzene	Benzoic acid + Benzyl
35		alcohol-Phenylacetic
36		acid + p-hydroxyethyl-
37		benzene
38 9	Propylene	Propylene oxide
39 10	Octane	Octan-1-ol
40 11	Phenol	Catechol + 1,4-dihy-
41		droxy benzene

TABLE XI (Continued)

<u>Conversion No.</u>	<u>Substrate</u>	<u>Oxidation Product(s)</u>
12	Pyridene	Pyridene-N-oxide
13	Toluene	Benzoic acid + hydroxy toluene
14	Styrene	Styrene epoxide
15	Naphthalene	1-Naphthol
16	iso Propyl benzene	4-methylbenzoic acid

Following generally the same procedure, propylene can be used as the substrate, as in Conversion No. 9, with methanol present in the circulating liquid medium as an electron donor.

The biocatalyst may be an enzyme preparation of any desired kind, including whole cells or crude or purified enzyme extract, immobilized in an inert inorganic or organic carrier. A preferred immobilized enzyme preparation is obtained by bonding cells to silanated glass beads using gluteraldehyde.

#### Biomass Production

The methane-grown microbial cells produced for use in the process of the invention possesses a high content of protein and can be used as such, as feedstuffs. Although methane is the preferred source of carbon and energy, the methylotrophic microorganism strains used in the present invention, including yeast strains, may also be grown on other methyl radical-donating, carbon-containing compounds, including methanol, methylamine, methylformate, methylcarbonate, dimethylether, and the like. This technique may be used for biomass production and also for regeneration of partially spent cells.

As is well known, in commercial processes for the production of microorganisms, it is generally necessary to proceed by stages. Ordinarily, propagation is started by inoculating cells from a slant of a culture into a presterilized nutrient medium usually contained in the flask. In the flask, growth of the microorganisms is encouraged as by shaking for aeration, and the maintenance



1 of suitable temperature. This stage is repeated one or  
2 more times in flasks or vessels containing the same or  
3 larger volumes of nutrient medium. The mass of microorgan-  
4 isms from the last stage, with or without accompanying cul-  
5 ture medium, is introduced into a large scale fermentor,  
6 in the conventional process, to produce commercial quan-  
7 tities of the microorganisms or enzymes from the  
8 microorganisms. In practising the present invention,  
9 the mass of microorganisms from the last culture  
10 development stage are grown up through the use of the  
11 continuous, countercurrent contact process described above,  
12 with concomitant oxidation of substrate.

13           The composition of the liquid phase for biomass  
14 production may typically consist of the solution of mineral  
15 salts described by Foster and Davis, J. Bacteriol, 91,  
16 1924-1931 (1966), and in Example 1 of GB 2,019,390 A.

17           The conditions of fermentation in the process  
18 of the present invention may be optimized to produce  
19 maximum yields of the microbial cells. Among the  
20 parameters that may be adjusted to this end are the selec-  
21 tion and concentration of nutrients, the pH, osmotic  
22 relationships, degree of aeration, temperature, and the  
23 like. It is also important to maintain the purity of  
24 the fermentation medium.

25           The fermentation is generally conducted at a  
26 temperature in the range from about 5°C to about 50°C,  
27 and preferably at a temperature in the range from about 25°C  
28 to about 45°C. Generally the pH is controlled to be in  
29 the range from about 4 to about 9, and preferably to about  
30 5.5 to 8.5, and most preferably from about 6.0 to about 7.5.  
31 The pressure employed during the fermentation must of  
32 course be adequate to permit the use of a countercurrent  
33 contact device, preferably a bubble cap tower.

34           When the objective is to produce cells, the  
35 oxidized substrate is recovered but is a by-product.

1 Conclusion

2           The invention in one embodiment is in a low-  
3 energy-requiring continuous process for carrying out the  
4 oxidation of a substrate tha is in either gaseous or  
5 liquid form. Higher pressure increases the solubility of  
6 gaseous substrates (i.e. gaseous hydrocarbons and oxygen)  
7 and stimulates the reaction of growth of microorganisms.  
8 The pressure can be adjusted by the adjusting depth of  
9 liquid in each tray and by designing the height of the  
10 bubble cap tower appropriately. If the pressure is too  
11 high, microbial growth may be affected. Therefore, the  
12 pressure is generally maintained at 1 to 5 atmospheres,  
13 preferably up to 2 atmospheres.

14           While a bubble cap tower is a preferred type of  
15 equipment, the oxidation processes can also be practiced  
16 in any other suitable type of equipment, such as, for  
17 example, an immobilized enzyme column. Also, the  
18 process practised need not be an oxidation process, but  
19 may be any process that utilizes a biocatalyst, such as,  
20 for example, isomerization, or one of the enzymatic  
21 processes described in the article by S. W. May, Enzyme  
22 Microb. Technol. 1979, Vol., 1, pp. 15-22, entitled  
23 "Enzymatic Epoxidation Reactions."  
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## CLAIMS:

1. A continuous biocatalytic process for the conversion of an organic substrate, comprising  
establishing a series of separate but inter-connected sequential contact zones,  
flowing a liquid composition comprising a biocatalyst successively through each of said zones from a liquid inlet zone to a liquid outlet zone,  
flowing a gas through each of said zones successively, from a gas inlet zone to a gas outlet zone, in intimate, countercurrent contact with the flowing liquid in each of said zones,  
flowing an organic substrate successively through each of said zones in intimate, reactive contact with said gas and with the liquid composition containing said biocatalyst, and  
recovering liquid effluent discharged from the liquid outlet zone and gaseous effluent discharged from the gas outlet zone,  
said recovered effluents comprising at least some of said organic substrate that has been converted to a different state.
2. A process according to claim 1 wherein the gas comprises a source of oxygen and the organic substrate is converted by the process to a more advanced state of oxidation.
3. A process according to claim 2 wherein the organic substrate is an oxidizable organic substrate and is in gaseous or vapor form, and is applied to the gas inlet zone for flow through said sequential contact zones with said oxidizing gas.

4. A process according to claim 3 wherein the substrate comprises ethylene that is converted to ethylene oxide.

5. A process according to claim 3 wherein the substrate comprises propylene that is converted to propylene oxide.

6. A process according to claim 2 wherein the organic substrate is an oxidizable organic substrate and is in liquid form, and is supplied to said liquid inlet zone for flow through said sequential contact zones with said biocatalyst liquid composition.

7. A process according to any one of the preceding claims wherein the biocatalyst comprises cells.

8. A process according to claim 7 wherein the biocatalyst comprises purified, immobilized enzyme.